

Passive Tag-to-Tag Communication

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Abstract— In this paper, we describe a novel passive RFID system capable of direct tag-to-tag communication in the presence of external radio frequency field. Tags talk by modulating the external field and thus backscattering the commands to each other. We present the system concept and show its hardware implementation based on TI MSP430 microcontroller. We also provide the theoretical model for modulation depth vs. distance which agrees with experimental results (maximum tag-to-tag communication distance). Finally, we discuss possible applications and outline future work.

I. INTRODUCTION

Over the past decade, UHF RFID has progressed significantly. Passive UHF RFID tags are emerging in use for many applications, such as tracking apparel and vehicles. The sensitivity for RFID tag ASICs have improved from -8dBm to -18 dBm [1-2] resulting in a three-fold read range improvement. And lastly, ISO 18000-6C (also known as “Gen2”) has been largely adopted as the UHF RFID protocol standard. Despite this progress, transacting with UHF RFID tags still requires a relatively expensive and power hungry RFID reader whose radio contains an active transmitter and a receiver with full-quadrature (IQ) demodulation.

In this paper, we demonstrate a novel system where tags can talk to each other directly in the absence of RFID reader as long as some external RF carrier source is available to power them up. Tags talk by modulating the field of that source - they backscatter commands to each other and decode them. If the carrier is strong, tags can be purely passive. If the carrier is weak, tags can be semi-passive (battery-assisted, or BAP), but they still talk to each other via modulated backscatter and contain no active RF transmitters. This is the fundamental difference from the active RFID tags based on such protocols as ZigBee, Bluetooth / Bluetooth Low Energy, ANT, DASH7, etc.

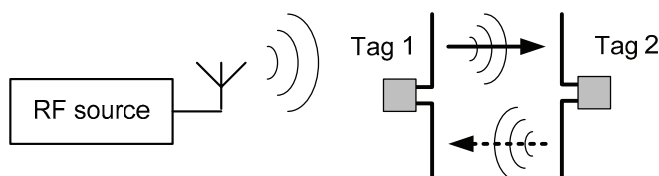


Figure 1. Concept of passive tag-to-tag communication system. Tag 1 sends data to tag 2 by backscattering RF CW signal from the external source. Tag 2 demodulates this signal and can respond to tag 1 in a similar manner.

The idea of tag-to-tag communication system was introduced earlier [3-4] and is illustrated in Fig. 1. The source which provides an external energizing field can be in the simplest case a constant wavelength (CW) source (see [5] for example of using such source). It can also be frequency hopping and contain some other modulation characteristics.

A good visual illustration of that system is an example of two persons in a dark room shown in Fig. 2. When the lights are turned off, those two persons cannot see each other. When the lights are turned on, the persons discover each other's presence because of the light which reflects from their faces and makes them visible to each other. The persons can now communicate using that external light by, for example, winking to each other using Morse code.

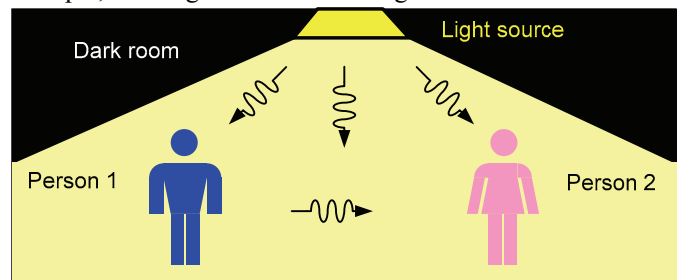


Figure 2. Illustration of passive tag-to-tag communication system.

There already exists a clear trend of adding more intelligence to both tags and readers to go beyond standard tag reading and writing protocol. For reader research, a very popular platform is Ettus USRP software defined radio platform [6]. For example, there are two interesting recent publications which describe RFID monitor [7] and RFID listener [8] which can receive and decode data exchange between the reader and the tag but do not initiate themselves any communications.

For tags, readily available low power microcontrollers provide an inexpensive way to implement custom tag architecture. Good examples of such microcontrollers are widely known WISP platform [9] and a recent work on the tag with backscatter diversity [10]. There also exist many works on hardware tag emulators [11-16] used for research on custom protocol, sensor, security, and other applications. In addition to that, there is now a variety of commercial battery-assisted UHF RFID ICs which have SPI or I2C interface to the microcontroller, allowing for additional sensor and security features [2, 17-19]. However, all custom tags mentioned above work entirely inside the conventional RFID paradigm where an active reader is interrogating a passive or semi-passive tag.

In this paper, we for the first time demonstrate in hardware the feasibility of a radically different system where passive or semi-passive tags talk to each other by modulating an external field. It is a communication system where all tag-to-tag links are backscatter based (we call it “passive”). Such passive tag-to-tag communication system can be, for example, peer-to-peer where tags have equal rights and can independently discover each other to initiate data exchange. In some sense, it is similar to the Tag Talks First (TTF) family of RFID protocols [20]. The tag-to-tag system can also be of master-slave type, where only one particular type of tag can initiate data exchange. In the latter case, the master tag can be programmed to act as a “reader” tag: to backscatter reader-type commands to tags around it while receiving and decoding tag ID and other data, thus reading the tags (slaves). Such system can readily work with existing Gen2 tags.

Since we work primarily with Gen2 RFID systems, we decided to concentrate on the latter “master-slave” type compatible with existing Gen2 tags. The master is the “reader” tag (RT) which contains no active RF transmitter but instead modulates its own antenna. The slave is a standard passive Gen2 tag, a.k.a. “listener” tag (LT), which responds to the commands originating from the “reader” tag.

The next sections are structured as follows. Section II is devoted to theory. Section III describes hardware implementation of the “reader” tag. Section IV contains experimental results. Section V draws conclusions, discusses possible applications, and outlines future work.

II. THEORY

A. Link budget

Many RF engineers find it convenient to work with link budget calculations of RFID systems using such quantities as incident power, tag antenna gain, impedance matching coefficient, etc. In Fig. 3, we illustrate the differences between conventional monostatic RFID system and tag-to-tag system using graphical link budget diagram. The diagram includes the RF transmitter (reader or CW source), the propagation channel, and the tags. The horizontal axis is distance, the vertical axis is power. Keep in mind that this diagram applies well to the far field situation (when readers/tags are far from each other) and free space environment (the loss in the propagation channel is log-linear, 20 dB/decade) but does not represent well near field interaction or multipath channels. Nevertheless, this diagram is useful to see the differences between conventional and tag-to-tag systems. In both systems, the power incident on the tag is

$$P_{inc} = P_t G_t G_{path} \quad (1)$$

where P_t is the output power of the reader, G_t is the realized gain of the monostatic reader antenna in the direction of the tag, and G_{path} is the propagation path gain. Let us assume that the tags in both systems are powered up (incident power exceeds tag sensitivity).

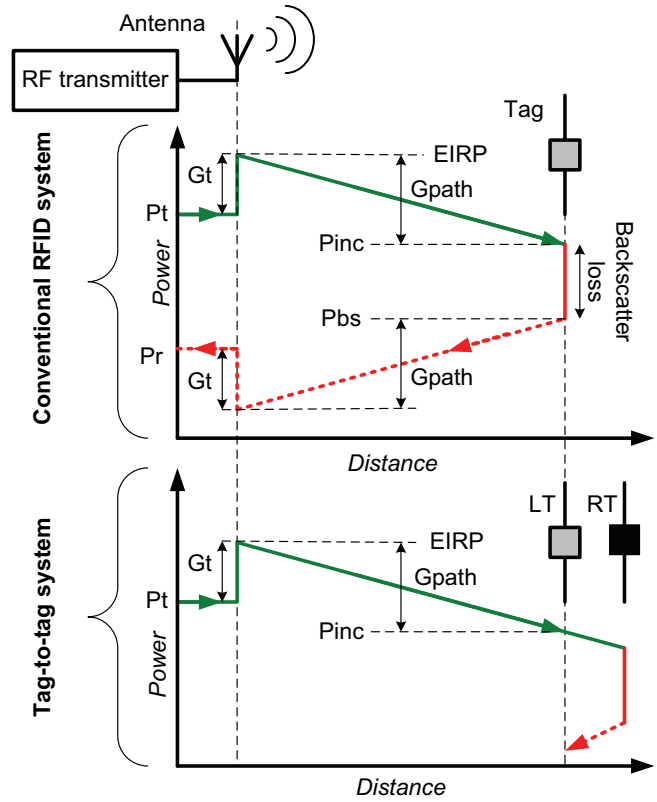


Figure 3. Graphical link budget diagram for conventional RFID system and tag-to-tag system.

In conventional system, the parameter that determines the reverse communication range (how far the reader can hear the tag) is the reader sensitivity which depends on self-jammer level and which must be better than the received tag signal P_r also known as RSSI [21]:

$$P_r = P_{bs} G_{path} G_t, \quad (2)$$

where $P_{bs} = P_{inc} K$ is the backscattered (modulated) power and K is the tag backscatter gain, sometimes also called modulation gain or conversion gain (a negative number).

In tag-to-tag system, the critical parameter which defines the tag-to-tag (RT-to-LT) communication range is the minimum voltage modulation depth m_{min} which LT tag needs to see in order to decode the command and respond. As soon as the modulation depth m of the signal becomes smaller

than m_{min} , the tag IC stops responding because it treats the demodulated signal with very low modulation depth as noise or as an invalid signal. An example demodulated signal inside tag IC (before the comparator) is shown in Fig. 4 (no waveform shaping is assumed). The received voltage toggles between two levels V_1 and V_2 due to two modulation states of the “reader” tag.

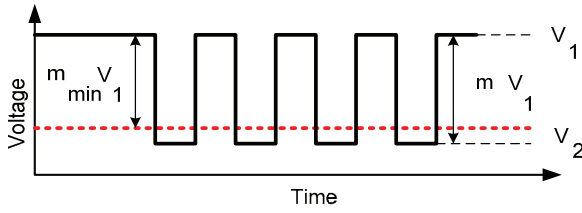


Figure 4. Example of demodulated voltage inside tag IC.

A condition when LT tag successfully decodes the signal and responds to RT tag can be written as:

$$m = \frac{V_1 - V_2}{V_1} \geq m_{min}, \quad (3)$$

Keep in mind that the superposition of signals from RF transmitter and from RT tag at LT tag terminals strongly depends on their individual phases which depend on mutual placement of RT and LT tags. The modulation depth of the RT tag signal rapidly decreases with separation between tags (see simulation results in subsection II D).

So far we only considered RT-LT link. The modulation depth required by the RT tag to hear LT tag may be different from the one required by the LT tag, so for reliable bi-directional communication equation (3) must be satisfied for both RT-to-LT and LT-to-RT links. Note that the minimum modulation depth required by the tag may be a function of incoming power, frequency, matching to the tag antenna, and waveshaping of the signal.

B. Near field coupling between tags

Our measurements (see Section IV) show that tags can only communicate in the close vicinity of each other. When two antennas of comparable size are located in the vicinity of each other (in the near field), the mutual coupling between the antennas affects the impedance of both antennas and the field distribution around them [22]. The equivalent antenna performance parameters (gain and impedance) can no longer be specified independently from each other and become strongly dependent on position and orientation of each antenna [23-25]. In general, to calculate the coupling between the antennas in such situation, one needs to perform a three-dimensional electromagnetic simulation of the whole problem [26] except for some isolated cases [27].

Near field coupling has previously been studied in RFID literature, both in application to near field reader antennas [28-29] as well as to closely coupled tags interrogated by the external reader [30-34]. In the latter works, the analysis usually concentrated on mutual coupling between the tags of various shapes (conventional dipoles, loops, T-matched dipoles, etc.) whose sensitivity to incoming reader signal is affected by their close proximity.

In all mentioned cases, tags are responding to the reader and do not talk to each other directly. The formalism usually applied is classical two-port Z-parameter (impedance)

matrix which relates voltages and currents on two closely coupled antennas. This classical formalism allows one to obtain an impedance of an antenna in the presence of another closely coupled and loaded antenna nearby [34]. However, the gain of the antenna also depends on the loading which means that one needs to run a full EM simulation for every case of a particular load value. Different possible tag antenna geometries also make electromagnetic modeling and simulation unavoidable.

As mentioned before, many RF engineers find it convenient to work with power quantities. Below, we describe a simple power-based theory which allows one to calculate the modulation depth of the signal produced by the “reader” tag as seen by the “listener” tag.

C. Modulation depth

Consider a scenario shown in Fig. 5 where the “reader” tag is placed near the “listener” tag. Since the antennas of two tags are closely coupled, they can be treated as a single antenna. When the modulator switch is on, the LT tag IC sees a combined antenna with impedance Z_{on} , and gain G_{on} . When the modulator switch is off, the LT tag IC sees a combined antenna with impedance Z_{off} , and gain G_{off} . Both gains are defined in the direction of incoming RF carrier. Those impedances and gains can be calculated for any geometry and shapes of the tag antennas using any conventional EM simulation tools.

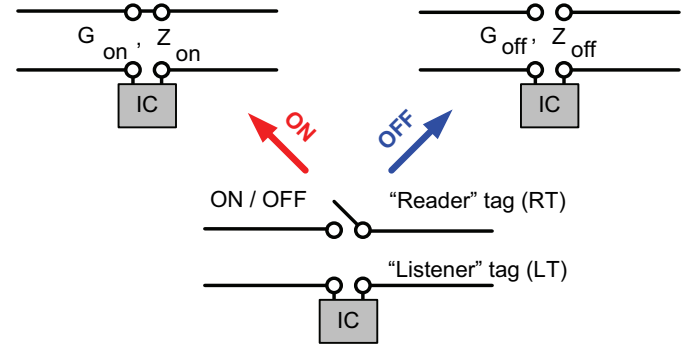


Figure 5. Two closely coupled antennas of RT and LT tags form a single antenna in each of the modulation states of RT tag.

Assuming for simplicity that both tags are polarization matched to the transmitter antenna, the power $P_{on,off}$ absorbed by the LT tag IC when the modulator switch is either on or off can be easily expressed as

$$P_{on,off} = P_{inc} G_{on,off} \tau_{on,off}, \quad (4)$$

where P_{inc} is the incident power at the tag location (see graphical link budget diagram in Fig. 3) and $\tau_{on,off}$ is the impedance matching coefficient between the tag chip with impedance Z_c and the antenna formed by the tag antenna and the modulated antenna:

$$\tau_{on,off} = \frac{4 \operatorname{Re}(Z_c) \operatorname{Re}(Z_{on,off})}{|Z_c + Z_{on,off}|^2}. \quad (5)$$

The voltage squared on the output of the AM demodulator (usually, a simple envelope detector) inside the tag IC is proportional to the power absorbed by the chip:

$$V_{on,off}^2 \propto P_{on,off}. \quad (6)$$

Thus the modulation depth can be calculated as:

$$m = \frac{|V_{on} - V_{off}|}{\max(V_{on}, V_{off})} = \frac{|\sqrt{G_{on}\tau_{on}} - \sqrt{G_{off}\tau_{off}}|}{\max(\sqrt{G_{on}\tau_{on}}, \sqrt{G_{off}\tau_{off}})}. \quad (7)$$

D. Simulation

We simulated a system two closely coupled straight dipoles shown in Fig. 6 using Ansoft HFSS. The dipoles were 130 mm x 2 mm copper traces on 60 mil Rogers 4003C material (substrate dimensions 140 mm x 20 mm). This is the same type of antenna that we used for our “reader” tag hardware implementation. One dipole (RT tag) is either shorted (modulator switch is on) or open (modulator switch is off). The input port of another dipole (LT tag) serves as an input port of a combined antenna. Assume also that this combined system of two dipoles is placed in the external RF field, and the input port of the system (LT tag port) is connected to hypothetical RFID IC with impedance of 50 Ohm.

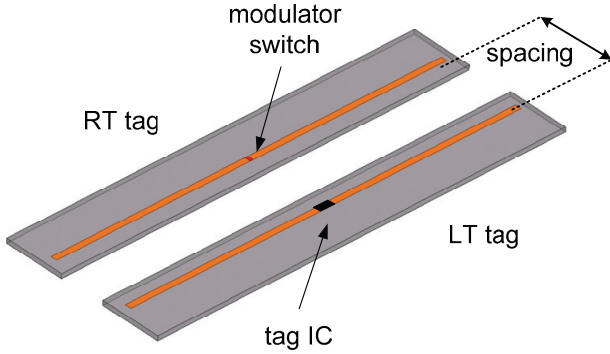


Figure 6. Two closely coupled dipole tags simulated in HFSS.

We obtained gain and impedance of such combined antenna for both states of RT tag (open and short) using Ansoft HFSS and then calculated the modulation depth as a function of their separation distance using Equation 7. In a similar fashion, one can calculate modulation depth for any tag-to-tag scenarios with arbitrary tag geometries and arrangements.

Fig. 7 shows that the modulation depth rapidly decreases with distance. One can see that the minimum modulation depth needed by the tag to respond is a critical parameter in tag-to-tag communication system, like tag sensitivity is critical in conventional reader-to-tag systems.

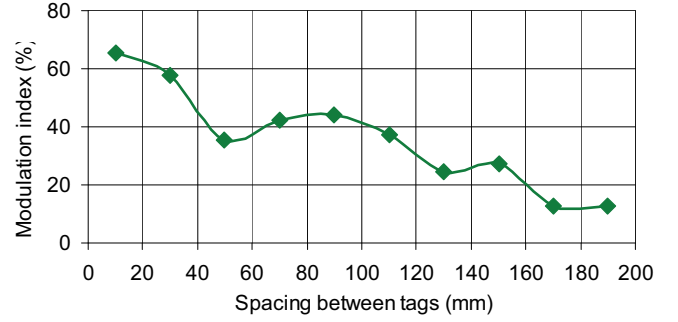


Figure 7. Modulation depth of the signal seen by the IC of LT tag as a function of separation distance between tags.

Gen2 specifications [35] dictate that readers must use modulation depth between 80% and 100%. At the same time, there exist publications on custom RF front ends for the tags responding to as low as 20% modulation depth of the incoming signal [36]. The smaller is m_{min} , the longer is tag-to-tag communication distance.

III. IMPLEMENTATION

A. System

The block diagram of our proof-of-concept tag-to-tag system is shown in Fig. 8. The “reader” tag (RT) modulates its own antenna with the Gen2 query. The “listener” tag (LT), which is a standard Gen2 tag, sees it and responds to that with its RN16. To make sure that Gen2 tag is indeed responding to the “reader” tag, a monitoring receiver (RF signal analyzer) is included into our system. This exchange of commands proves the bi-directionality and the feasibility of such tag-to-tag communication system.

For generating RF CW signal, we used Agilent 8648C generator which is one of many standard RF signal generators. The receiver was connected to the transmitting antenna via an RF circulator (M/A Com 7N195). To be able to conduct tests at various power levels we also included RF power amplifier (Comtech AM88258-10). For monitoring any backscatter activity on the air, we used National Instruments PXI-5660 RF signal analyzer. National Instruments PXI RF instruments are in general a popular choice among RFID researchers due to their flexibility [37] although in recent years several other commercial products have appeared [38].

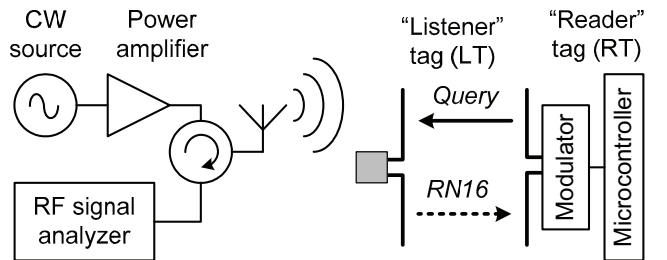


Figure 8. Block diagram of the proof-of-concept passive tag-to-tag communication system.

B. “Reader” tag (RT)

The block diagram of the “reader” tag is shown in Fig. 9. The “reader” tag was built using TI MSP430F5529 ultra-low power microcontroller [39] chosen by us because it can operate on low supply voltage (1.8 to 3.6 V) and has a number of features such as USB 2.0 connection and a 12-bit analog-to-digital converter (ADC) which can be used in future for demodulating and processing the tag response.

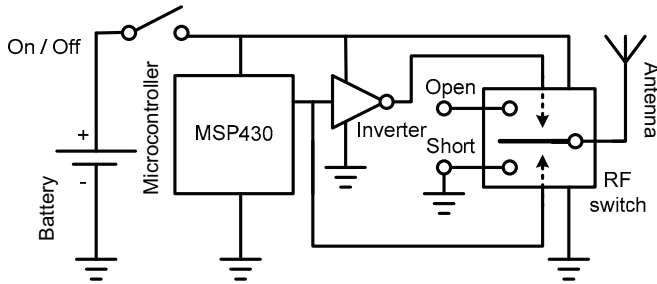


Figure 9: Block diagram of the “reader” tag.

The microcontroller was mounted on 54 mm x 85 mm (credit card sized) PCB board with some minimal peripheral components that support microcontroller operation. In general, a “reader” tag can be either powered by its own battery or by harvesting external RF energy. For the simplicity of debugging, we decided to use a battery to power up the microprocessor and modulator. We used a standard Panasonic BR3032 coin cell battery with 500 mAh capacity and included an On/Off switch on our “reader” tag board. The prototype is photographed in Fig. 10, where the “reader” tag is placed for comparison next to the “listener” tag (a standard Gen2 tag), just like it would be done during our tests.

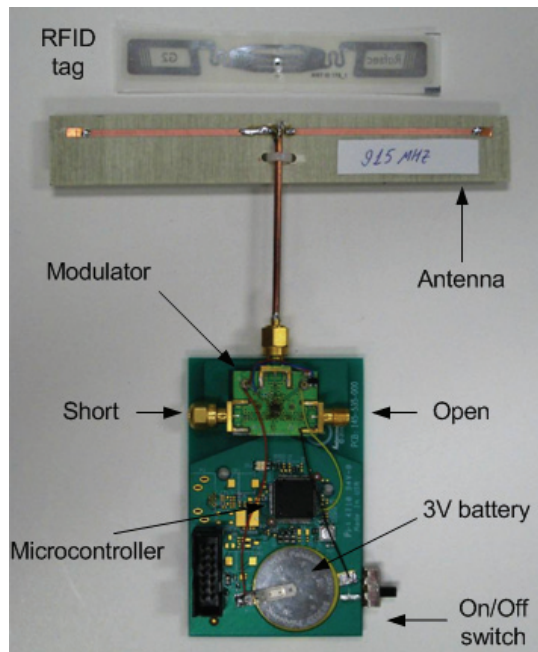


Figure 10: Photograph of the prototype “reader” tag next to the “listener” tag.

We programmed the microcontroller to generate a *Query* command from Gen2 INVENTORY group [35] to which all of the tags used in testing (see Section IV) successfully responded. The command used in testing was **1000000100100000011100** with the following parameters:

- $T_{ari}=24 \mu s$, $Pulsewidth=0.5 T_{ari}$
- $RT_{cal}=2.5 T_{ari}$, $TR_{cal}=3 RT_{cal}$
- $DR=8$ (backlink frequency 44.44 kHz)
- Tag backscatter encoding: FM0 ($M=1$)

The total transmission, shown in Fig. 11, was 5 ms long and was repeated continuously back-to-back.

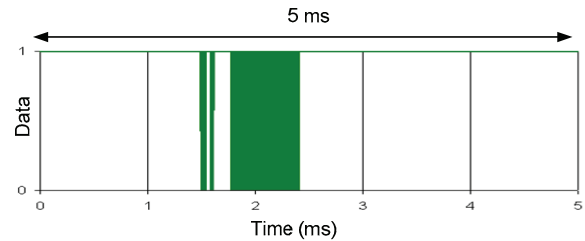


Figure 11. Query command generated by the microcontroller.

For the RF switch which modulated the antenna, we decided to use discrete voltage controlled switch (as oppose to a single modulating transistor) in order to have convenience and flexibility when experimenting with different modulation loads and antennas. We used Hittite Single Pole Dual Throw (SPDT) HMC545 switch [40]. This is a low cost switch typically used in RF applications which require low insertion loss and small size. To generate opposite control voltage signals for switching we used a standard CMOS inverter IC (MC74). The switch was mounted on a separate PCB with three SMA ports (two for the loads and one for the antenna).

For the antenna, we used a dipole antenna. It couples well with Gen2 tags most of which also use dipole-like antennas. Other advantages of dipole antenna are that it is simple, compact, has reasonable gain (about 2 dBi) and doesn’t significantly block the line of sight if placed between the RF transmitter and the “listener” tag. Since both LT and RT tags are in the near field of each other, higher gain antenna on RT tag would not necessarily help to improve the coupling. We designed and built a dipole antenna on 60 mil Rogers 4003C material (substrate dimensions 140 mm x 20 mm, antenna trace dimensions 130 mm x 2 mm). The antenna was tuned to 915 MHz. It is the same antenna that was modeled and simulated with Ansoft HFSS as described in previous section.

IV. EXPERIMENTS

A. Verifying HFSS simulation of coupled dipoles

To confirm that our EM simulations of two dipole coupled system were correct, we built an experimental setup (shown in Fig. 12) using two identical dipoles (same as the one used by our “reader” tag) and measured S- and Z-parameters for various spacing. The agreement between measurements and HFSS was very good as shown in Fig. 13 for one of the spacing values (25 mm).

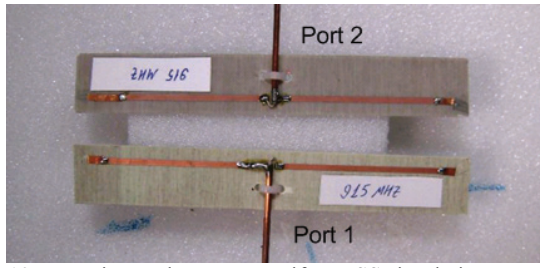


Figure 12. Experimental setup to verify HFSS simulation.

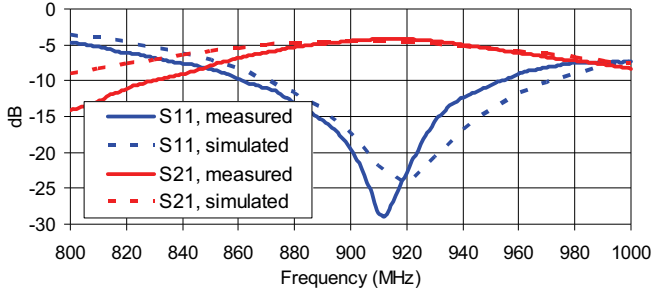


Figure 13. S-parameters of the two coupled dipoles shown in Fig. 12 with 25 mm spacing (measurement vs. simulation).

B. Measuring tag-to-tag communication distance

As soon as we placed both “listener” tag and our “reader” tag next to each other in the field of RF source, we clearly observed on RFSA that LT tag was responding to RT tag modulation. The key parameter we were interested in was the maximum communication distance between the tags. To explore it further, we performed several measurements with:

- various antennas on the external RF power source (2 dBi dipole, 6 dBi patch, 6 dBi log-periodic);
- various power levels of the external RF power source (between 10 dBm and 30 dBm);
- various distances between the transmitting antenna and the tags (1 ft to 10 ft);
- various mutual arrangements of “reader” and “listener” tags;
- various spacing between the “reader” tag and Gen2 tags (between 1 and 100 mm);
- various Gen2 tags used as “listener” tags;
- various environments (chamber, office cubicle).

Below we describe one typical experiment. The setup included an anechoic chamber and a 6 dBi linearly polarized antenna (Sinclair SRL441U) driven by 915 MHz RF generator with an amplifier as shown in Fig. 8. The power into the antenna was 20 dBm which was enough to power all our Gen2 tags placed 3 ft away from the antenna. The “reader” tag was placed at various distances directly behind the “listener” tag as shown in Fig. 14.

As “listener” tags, we used four typical Gen2 tags shown in Table I. Their sensitivities and minimum modulation depths were measured using our wideband NI equipment [37] in the same setup (shown in Fig. 14) and are given for 915 MHz. Three tags (AD-431, Rafsec Hammer and G2) were based on Impinj Monza 2 IC and one tag (AD-223, very popular choice in warehouse environment) was based on Impinj Monza 3.

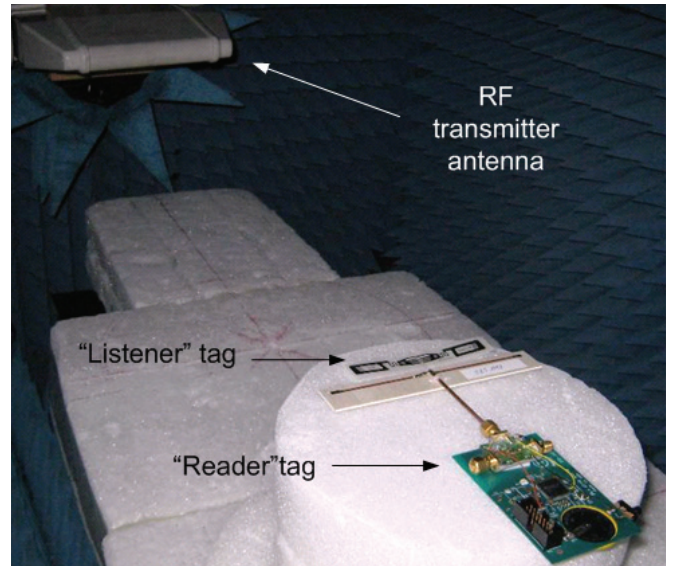


Figure 14. Photograph of the experimental setup.

TABLE I. GEN2 RFID TAGS USED IN MEASUREMENTS.

Tag	Chip	Tag sensitivity	Minimum mod. depth
AD-431	Monza 2	-12.3 dBm	39 %
Hammer	Monza 2	-12.9 dBm	43 %
G2	Monza 2	-12.2 dBm	54 %
AD-223	Monza 3	-15.8 dBm	48 %

Each of the tags in Table I responded to the modulation query produced by the “reader” tag. A typical observed envelope demodulated voltage on the output of the RFSA receiver is shown in Figure 15 for the case when the “reader” tag was 25 mm behind the “listener” tag (Rafsec G2 tag) as shown in Fig. 14. The tag RN16 response to the query from the “reader” tag can clearly be seen.

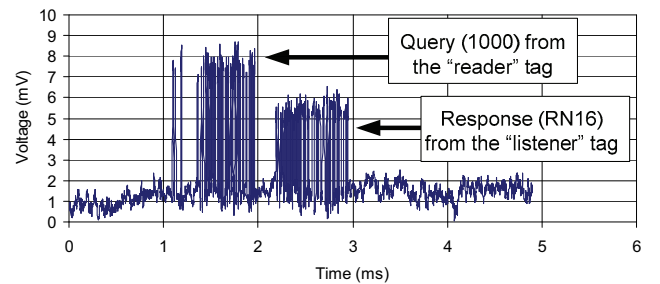


Figure 15. “Reader” tag modulation query and “listener” tag RN16 response to it, both captured on RFSA.

We observed in our experiments that in most cases the maximum reliable tag-to-tag communication distance did not exceed 1 inch (25 mm). It depended on the “listener” tag, tag, its arrangement relative to the “reader” tag antenna, and their mutual orientation/placement with respect to the direction of the incident RF power signal. In some isolated cases we were able to observe LT tag responding even when RT tag was about 4 inches (100 mm) away, but those cases were hard to reliably reproduce and were usually observed in the vicinity of the transmitting antenna, when RT and LT tag antennas were at approximately 45 degree angle to each other.

Overall, we found that the tag-to-tag communication system is very sensitive to the mutual arrangement of the RT and LT tag antennas. Slight change in position could cause the LT tag not to respond to the RT tag, but another slight change in position would cause it to respond again. This behavior is different from conventional RFID systems where tags can move around but as long as they remain powered up, RFID reader can detect them.

It can be understood if one recalls the architecture of RF receivers in conventional RFID reader and RFID tag shown in Fig. 16 (only the receivers are shown). The reader has a fully coherent quadrature receiver while the tag receiver only has an incoherent power detector. When RT tag modulates an external RF field, RFID reader receiver sees a constellation of two points on IQ diagram. As the RT tag is moved around, the constellation changes and the signal shifts between I and Q components but always remains present on at least one of the I or Q channels. On the other hand, the LT tag receiver sees the demodulated signal proportional to $\sqrt{I^2 + Q^2}$. As the RT tag modulator is moved, the constellation can change so that the modulation appears to be mostly in phase which cannot be detected by the power detector in LT tag.

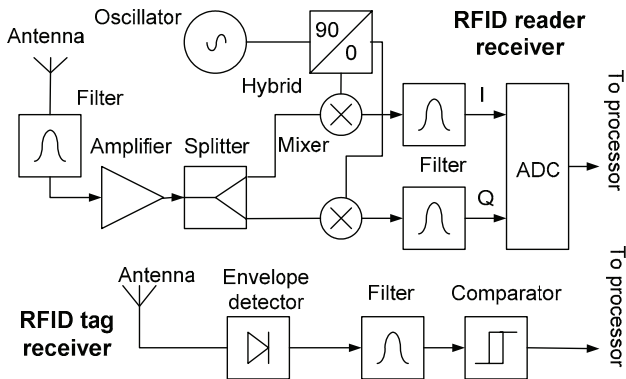


Figure 16. Block diagrams of receivers in RFID reader and RFID tag.

Our measurements (Table I) show that Gen2 tags needed on the order of 40% to 60% minimum modulation depth in order to respond. Fig. 7 (simulation) shows that the modulation depth between two collinear identical dipoles (one of which is loaded with 50 Ohm IC) becomes smaller than 60% roughly at 30 mm spacing. This generally agrees with the maximum tag-to-tag communication distance of 25 mm which we observed in our experiments.

V. CONCLUSIONS

In this paper, we for the first time demonstrated in hardware a feasibility of RFID tag-to-tag communication system, where passive or semi-passive tags or their combinations talk to each other by modulating an external field. Because the antenna modulating process in tags does not require active RF transmitters which are the main power consumers in radios, the battery life can become very long (for battery assisted tags) or indefinite (for passive tags). This allows one to build a short range reader module which can easily be integrated into various devices and has low cost and low power consumption. Those two characteristics represent clear advantages of tag-to-tag communication system in comparison with conventional RFID system. The disadvantage of the tag-to-tag system is that an external RF power source must be provided.

There are many potential applications of the tag-to-tag communication, all originating from the fact that passive (or semi-passive) tags/sensors can use the presence of external RF carrier to convey messages to each other. For example, imagine RFID “reader” tag in the form factor of a credit card as shown in Fig. 17. The “reader” tag card may include an on/off switch, status LEDs, USB port, and LCD display which shows the IDs of the read tags.

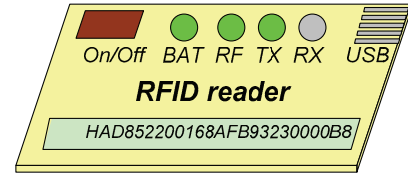


Figure 17: Concept RFID “reader” tag in a credit card shape.

Other possible form factors may include peripheral attachments to your mobile phones, flexible bracelets, etc. Imagine that you would be able to wear a thin flexible passive batteryless bracelet (see Figure 18) which will “remember” all the tagged hands which you shook during the day (*person-to-person*) and all the tagged objects which you touched (*person-to-object*) as well as their characteristics obtained from the built-in tag sensors. A person would be able to retrieve that data from the “reader” tag using either wired or wireless connection. Tagged objects will also be able to get to know their neighbors (*object-to-object*).

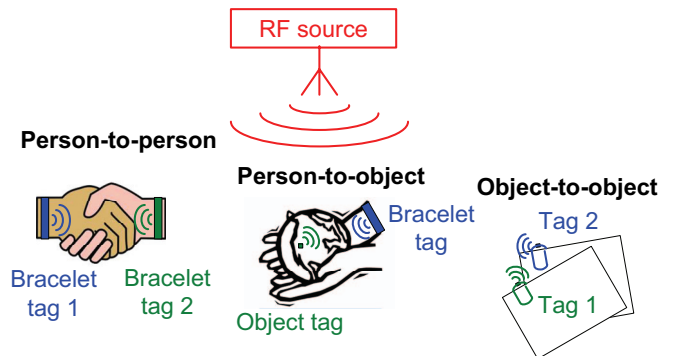


Figure 18: Sensing applications of tag-to-tag communication.

The tag-to-tag communication system is based on power detection of signals, and both “listener” and “reader” tags are sensitive to the amplitude modulation depth. Both of these facts add challenges to reliable detection and decoding. The communication distance can be improved if active RF receiver is added to the “reader” tag but this will bring the cost of increased power consumption. Another potential improvement can come from using separate antennas for collecting RF power and for backscatter modulation [41]. Below is an outline of some of the future work which we see:

- Experimentally characterize minimum modulation depth in different tags as a function of power, frequency, etc.;
- Measure the maximum RT-to-LT tag communication distance in a variety of controlled scenarios;
- Simulate modulated depth vs. distance for specific LT tags (antennas and ICs) and compare with measurements;
- Add detector and demodulator to the “reader” tag;
- Add decoder to MSP430 to read LT tag IDs;
- Integrate RT tag antenna and electronics on a single PCB;
- Build simple RF power transmitter compliant with FCC;
- Make batteryless “reader” tag with RF power harvester;

All in all, we believe that the concept of passive tag-to-tag communication system opens an interesting field which will need research in all areas, including applications, antennas, circuits, protocols, and systems.

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